Effects of Kenaf Fiber Orientation on Mechanical Properties and Fatigue Life of Glass/Kenaf Hybrid Composites

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The objectives of this work were to investigate the effect of kenaf fiber alignment on the mechanical and fatigue properties of kenaf/glass hybrid sandwich composites. Three types of kenaf fibers were used, namely, non-woven random mat, unidirectional twisted yarn, and plain-woven kenaf. A symmetric sandwich configuration was constructed with glass as the shell and kenaf as the core with a constant kenaf/glass weight ratio of 30/70% and a volume fraction of 35%. Tensile, compression, flexural, and fully reversed fatigue tests were conducted, and a morphological study of the tensile failure surface of each hybrid composite was carried out. The non-woven mat kenaf hybrid had poor properties for all tests, while the unidirectional kenaf hybrid composite possessed higher tensile strength and similar compressive properties compared with the woven kenaf. Hybridization with kenaf fibers improved the fatigue degradation coefficient of the final composites to 6.2% and 6.4% for woven and unidirectional kenaf, respectively, compared with 7.9% for non-woven. Because woven kenaf hybrid composite is lightweight, environment friendly, and has a considerable balance in static and fatigue strengths with low fatigue sensitivity in bidirectional planes compared to glass, it is strongly recommended for structural applications.

Keywords: Glass; woven; Non-woven; Unidirectional kenaf; Natural fibers; Hybrid composites; Mechanical properties

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INTRODUCTION

The environmental advantages of using natural fibers instead of glass fibers as reinforcement for composite materials are well known (Adekunle *et al.* 2011; Rassmann *et al.* 2011; Ratna Prasad and Mohana Rao 2011). In the automotive industry, natural fiber composites reduce toxin emissions and improve fuel efficiency. It has recently been estimated that substituting natural fibers for 50% of the glass fibers used in automotive applications in the USA would eliminate 3.07 million tons of carbon dioxide emissions and 1.19 million m^3 of crude oil consumption by 2020 (Davoodi *et al.* 2010). Natural fibers such as hemp, jute, sisal, and kenaf are lighter, low-cost materials with highly specific mechanical properties that can reduce the density of a composite by 10 to 15% compared

with glass fiber; additionally, natural fibers are compatible with the most commonly used polymers including polyester, epoxy, and vinyl-ester (Jawaid and Abdul Khalil 2011).

When two or more fibers are combined in a single matrix, creating a final material called a "hybrid composite", the behavior of the hybrid composite ideally is expected to be the sum of the behaviors of the individual fibers used, such that there is a balance between the advantages and disadvantages of both reinforcements. Many parameters affect the strength of hybrid composites including fiber content, fiber-matrix interface bonding, fiber orientation, sequence configuration of both fibers, and failure strain of the fibers (Jawaid and Abdul Khalil 2011; Mishra *et al*. 2003). The prime factors in producing hybrids are the individual fiber properties and their compatibility. In addition, the application and loads that will be imposed on the material define the purpose of hybridization and determine the final product (John and Thomas 2008; Salman *et al.* 2015a).

Hybridization of natural fibers with glass for reinforcement of unsaturated polyester has been extensively studied with different fiber loadings and structures under various loading conditions. A few studies on the hybridization of natural-glass fiber hybrid composites used as reinforcement in unsaturated polyester are reviewed below.

Abedin *et al.* (2006) studied the effect of hybridization of jute/glass fiber hybrid-reinforced unsaturated polyester composites. The results showed improvements in tensile strength and modulus of 125% and 49%, respectively. In addition, the flexural strength and modulus were 162% and 235% higher, respectively, by using a jute-to-glass ratio of 1:3 compared with those of plain jute composites. Among all the fabricated hybrid composites, the hybrids with natural synthetic fiber ratios of 1:3 resulted in better compressive composite properties. Thus, increasing glass loading in composites increases the compressive and inter-laminar shear strength properties of hybrid composites. Higher flexural and compressive properties have also been found for kapok/glass hybrid composites as compared with kapok/sisal composites (Reddy *et al.* 2008).

Ornaghi *et al.* (2010) investigated the impact and flexural properties of sisal/glass hybrid composites using different volume fraction ratios of hybrid composites through different ratios of both fibers in order to determine the optimum properties of the hybrid composite. Dieu *et al.* (2004) studied the mechanical properties of bamboo/glass hybrid composites fabricated by compression molding. The total fiber weight fraction was 25% using different bamboo/glass fiber ratios, and the best hybrid composite properties were exhibited with a bamboo/glass ratio of 1:3.

Another study (Pothan *et al.* 2007) investigated the effect of sequence configuration of banana/glass hybrid composites on water absorption. The water absorption of hybrid composites was affected significantly by the sequence of layers, and the best layering pattern was a sandwich configuration (glass as the shell and banana as the core).

The thermal conductivity and tensile and flexural properties of sisal/glass fiber hybrid composites were also studied (Naidu *et al*. 2011a,b). A better performance in the overall properties of sisal/glass fiber hybrid composites was found. John and Naidu (2004) studied the deviations of compressive strength in sisal/glass unsaturated polyester hybrid composites with fiber loading; chopped strand fibers were used to fabricate the composites. The glass/sisal fiber volume ratio of 75/25% had a higher compressive strength compared with other hybrid composites. Khalil *et al.* (2007) investigated the mechanical and physical properties of oil palm empty fruit bunch/glass hybrid-reinforced polyester composites as well as the hybrid effect of glass and empty fruit bunch fibers on the tensile, flexural, impact, and hardness of the composites. They concluded that hybrid composites exhibited good properties compared with the empty fruit bunch/polyester composites.

Recently, Atiqah *et al.* (2014) developed chopped strand mat (treated and untreated) kenaf-glass fiber-reinforced unsaturated polyester hybrid composites fabricated using a sheet molding compound process for structural applications. In this study, the fiber volume was kept at 30%, and the kenaf to glass volume ratio was changed. A 15/15 volume ratio of treated kenaf/glass hybrid composites exhibited the best properties. Bakar *et al.* (2015) investigated the effect of fiber treatment on long unidirectional (UD) kenaf/woven Kevlar hybrid composites on tensile and low impact properties. The results revealed an improvement in interfacial adhesion that led to better mechanical properties.

A few works have reported on the cyclic fatigue assessment of natural-synthetic hybrid composites. Thwe and Liao (2003) investigated the effect of hybridization on the durability of bamboo/glass-reinforced polypropylene hybrid composites in a sandwich sequence. While the results regarding the fatigue of hybrid composites were limited, it was concluded that the hybridizing process improved the fatigue life of bamboo-based composites. Bagheri *et al.* (2014) studied the fatigue life of unidirectional flax/carbon-reinforced epoxy hybrid composites for medical applications. In this study, a non-destructive method using an IR-camera and morphological assessment was used to predict the high cyclic fatigue strength of the hybrid composites. Although no comparison with pure flax or carbon fiber-based composites was available, an improvement in fatigue strength was found compared with previous work on pure flax.

Shahzad (2011) reported on the hybridization of chopped mat hemp fibers and glass as reinforcements for unsaturated polyester and the fatigue strength of the composites; the hybrid composites were fabricated in a sandwich configuration. Though the fatigue strength of the composites was enhanced by adding glass fiber, no improvement in fatigue sensitivity was observed.

Notably, there have been very few reports on the effect of fiber orientation and, especially, fatigue life of kenaf/glass hybrid composites. In the present work, a hybrid composite was developed by combining natural and synthetic fibers with different kenaf orientations in a sandwich configuration. The kenaf fibers were non-woven random mat, unidirectional twisted yarn, and plain-woven fabric kenaf.

The hybrid composite had a constant kenaf/glass weight ratio of 30/70 % and an approximate volume fraction of 35%. The tensile, compressive, and flexural properties were determined. The fatigue life, stiffness degradation, and high cyclic regime of the composites were also characterized in order to recommend the optimum hybrid composite for structural applications.

EXPERIMENTAL

Materials

The three types of kenaf used as reinforcements—non-woven random mat, unidirectional twisted yarn, and biaxial woven kenaf fabric—were supplied by ZKK Sdn. Bhd, Malaysia. The fibers were placed in a ventilated oven to remove the moisture before fabricating the composites.

The synthetic reinforcing fiber was woven roving glass EWR 400. Orthopathalic unsaturated polyester was used as the binding resin, which was mixed with 1.5% wt. of Butanox M50 as a catalyst. Figure 1 shows the materials used in the kenaf/glass hybrid composite laminates, and their specifications are tabulated in Table 1 (Kistaiah *et al.* 2014; Salman *et al.* 2015b).

Table 1. Properties of the Reinforcements and Resin

Properties	Materials		
	Kenaf	Glass	Unsaturated Polyester
Density (g/cm^3)	1.2	2.5	1.14
Yarn Breaking Load (N)	79	2500	-
Breaking Strength (MPa)	100.64	2400	69
Elongation (%)	17.3	3	2.3
Elastic Modulus (GPa)	23	50	3.8
Moisture Absorption (%)	8.3	0.12	0.02

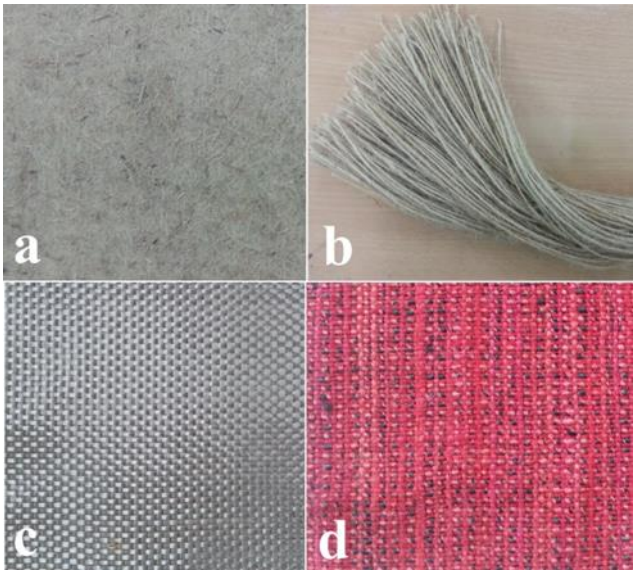

Fig. 1. Fiber reinforcements. (a) Non-woven kenaf mat, (b) unidirectional twisted yarn kenaf, (c) plain woven E-glass, and (d) plain woven kenaf

Fabrication of the Composites

A combination of the hand lay-up and hydraulic cold press methods was used to fabricate the hybrid composite laminates. The three types of kenaf were placed in a ventilated oven at 105 °C for 24 h to remove the moisture. The unsaturated polyester was mixed with 1.5% catalyst and then poured onto each layer of fabric; a roller was used to separate the resin along the layers and remove air bubbles. For the unidirectional kenaf, the long fibers were carefully aligned over the glass to minimize disorientation of the fiber. After laying-up the reinforcements, the mold was closed and placed under cold pressing for 1 hour followed by post curing inside the oven for 2 h at 80 °C, which is the curing temperature of unsaturated polyester. Finally, the reinforcements were cured at room temperature for 48 h before the composites were cut into the required dimensions for testing. The fiber volume fraction of the composites was kept at approximately 35%. The glass/kenaf weight ratio selected in this study was 70:30, which is the optimum glass/kenaf hybrid fiber composition (Dieu *et al.* 2004; Wan Busu *et al.* 2010; Mansor *et al.* 2013) in a symmetric sandwich configuration.

The experimental density of the composites was measured using distilled water and standard ASTM D-792 (1991). A sensitive digital balance with three significant figures was used. Five samples were measured, and the average value was recorded. The void contents of the composites were determined using Eq. 1 (Dhakal *et al.* 2007),

$$Void\ content\ (\%) = 1 - \rho_c \left[\frac{w_{f1}}{\rho_{f1}} + \frac{w_{f2}}{\rho_{f2}} + \frac{w_m}{\rho_m}\right] * 100\ \% \quad (1)$$

where W_f and W_m are the weight fractions of the fibers and the matrix, respectively, and ρ_c, ρ_f, and ρ_m are the densities of the composite, fibers, and matrix, respectively. The fiber volume fraction of the hybrid composites was calculated using Eq. 2,

$$v_f\ (\%) = \left[\frac{\left(w_k/\rho_k\right)+\left(w_g/\rho_g\right)}{\left(w_k/\rho_k\right)+\left(w_g/\rho_g\right)+\left(w_m/\rho_m\right)}\right] * 100\ \% \quad (2)$$

where W_k, W_g, and W_m are the weight fractions of the kenaf, glass, and matrix, respectively. In addition, ρ_k, ρ_g, and ρ_m are the densities of the kenaf, glass, and matrix. Table 2 shows the designation, composition, and specifications of the composite laminates.

Table 2. Designation and Composition of the Hybrid Composites

Fiber Type	Fibers Weight Ratio (%)		Fiber Fraction (%)		Density (g/cm³)	Void Content (%)	Fatigue Coefficient *b*	Thickness (mm)
	Glass	Kenaf	Weight	Volume				
Woven	71.7	28.3	49.7	37.5	1.41	1.4	-0.06186	3.15
NW	71.2	28.8	45	33.6	1.31	5.9	-0.07938	4.18
UD	71.1	28.9	51.7	38.7	1.39	3.5	-0.06486	3.03
Glass	100	0	58.3	38.8	1.66	1.2	-0.05995	2.32

Testing Procedures

Tensile

Tensile loading condition was investigated using a universal testing machine (model 3382 with Bluehill software, Instron, USA) equipped with a 100 kN load cell with a cross-head speed of 2 mm/min. The composite laminate samples were cut using a circular saw, and the edges were smoothed and finished to the required dimensions. The dimensions (250 mm in length, 25 mm in width, and 170 mm in gauge length), sample preparation, and test procedure were followed according to standard ASTM D-3039 (1995b). Six specimens were tested for each group of composite, and values were averaged and recorded.

Compression

The compressive strength of the composites was determined using an Instron machine 3382 equipped with a 100 kN load cell and cross-head speed of 1 mm/min according to standard ASTM D-3410 (1995a). Six samples with dimensions of 120 mm in length, 25 mm in width, and gauge length of 13 mm were tested for each composite. The gauge length was reduced to a minimum to prevent buckling during compression loading. The average of the five best values of compressive strength was recorded as the final compressive strength.

Flexural

Three-point bending testing was carried out with an Instron machine (model 3366 with Bluehill software, Instron, USA) with a 5 kN load cell and cross-head speed of 2 mm/min according to standard ASTM D-790 (1997). The tests samples were carefully cut from each laminate to the required shape using a wheel saw. Five rectangular specimens with dimensions of 130 mm in length and 13 mm in width were tested for each composite. The span-to-depth ratio was 16:1, and the average value was determined and recorded.

Fatigue

The fatigue test procedure was conducted according to ISO 13003 (2003). Twelve fatigue specimens with dimensions of 120 mm by 25 mm with the minimum gauge length to prevent buckling were prepared and glued to aluminum tabs with a thickness of 1.5 mm. A fully reversed (tension-compression) cyclic loading test was performed using a servo-hydraulic universal testing machine (model 8874 with wave matrix fatigue software, Instron, USA) equipped with a 30 kN unit cell under load control, with a selected stress ratio of (-1) and a frequency of 10 Hz. The test was performed at four stress levels: 40, 50, 60, and 70% of the static ultimate stress of the composite. In addition, an IR thermographic camera (Flex-Cam model Ti45, Fluke Corporation, WA, USA) with a detector resolution of 160 × 120 and a 20-mm lens was used to monitor the specimen temperature during fatigue testing as recommended by the standard. A power-law regression equation was used to fit the experimental fatigue data to determine the fatigue coefficients of the materials *b* after plotting the Wohler stress-life (S-N) diagram (Eq. 3),

$$\sigma_{max.} = \sigma_0 N^b \quad (3)$$

where σ_{max} is the maximum applied stress, σ_0 is the static ultimate strength, N is the number of cycles to failure, and b is the fatigue strength coefficient.

Morphological

A scanning electron microscope (SEM) was used on selected failed samples in order to study the morphological behavior of tensile failure sections, and also to get more details about the fracture modes for the different structures of the kenaf used. In addition, the SEM shows the compatibility between the glass, kenaf fibers, and unsaturated polyester matrix. The experiments were conducted using a model S-3400N PC-based variable pressure SEM (Hitachi, Japan).

RESULTS AND DISCUSSION

Static Properties

Tensile strength testing showed that the stress-strain curves for hybrid composites were linear along their elastic zone, until the ultimate strength point, at which a sudden drop in load and catastrophic fracture occurred. This result confirmed the strain compatibility of kenaf and glass, which is an important parameter for designing hybrid composites (John and Thomas 2008). Of the composites tested, the unidirectional kenaf/glass hybrid composite possessed the best tensile properties, with only a 36% reduction in tensile strength, and 39% reduction for woven kenaf compared with pure glass composites (Fig. 2). These results reflect the kenaf fiber placement parallel to the loading plane direction and, furthermore, the concentration of kenaf bundles into the main load

carriers. Though the unidirectional fibers showed high strength in the parallel plane, they had lower strength in the normal loading plane (Yahaya *et al.* 2014a).

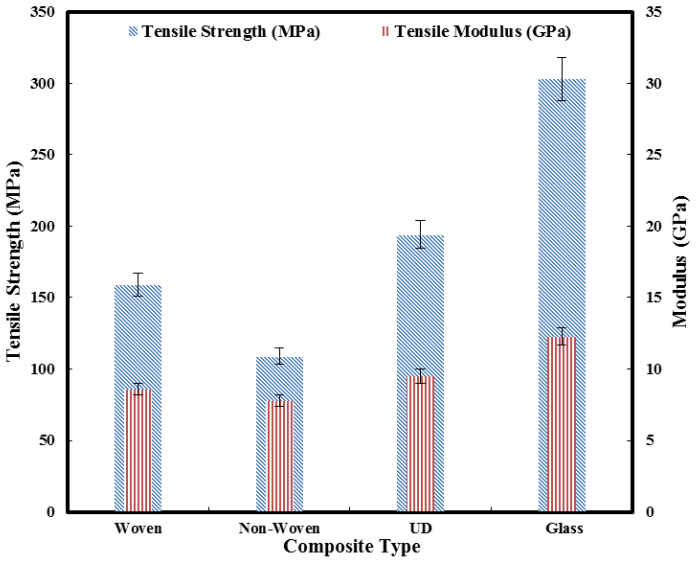

Fig. 2. Tensile properties of composites

The random mat kenaf/glass hybrid composite showed similar stress-strain performance and a brittle failure mode with sudden fracture, but it offered low tensile strength and modulus compared to the UD and woven kenaf. This effect was attributed to the short kenaf fibers and the absence of interlocking fibers, making the matrix the main load carrier. Moreover, the presence of voids also affects tensile strength in composites (Aji *et al.* 2011; Hojo *et al.* 2014). The strain at breakage of the non-woven kenaf was lower (1.65%) than that of the UD and woven kenaf (2%); this value varies depending on the general fracture mode and the main load carrier of the composite. To form continuous fibers, natural fibers are processed, e.g., by twisting, which could reduce mechanical properties of the composite (Shah *et al.* 2012a).

The woven kenaf/glass hybrid composite displayed a considerable balance in tensile properties. The advantage of woven kenaf is the ability to show similar strengths in the biaxial direction of loading compared to the unidirectional fiber. This effect is attributed to the mesh structure of kenaf, which offers more flexibility to transform the stresses to fiber bundles (Yahaya *et al.* 2014b).

Generally, the alignment of kenaf fibers in unidirectional, and fiber density along the composite laminate is difficult to manage compared with plain-woven kenaf, which has a uniform fiber distribution. This parameter can increase the scattering and deviation of replicate results (Shah *et al.* 2012b). Notably, the values reported in the present study were higher in terms of strength and modulus compared with previous studies that used chemically treated and untreated, UD and random mat kenaf/glass hybrid composites (Ya'acob *et al.* 2011; Ghani *et al.* 2012; Atiqah *et al.* 2014).

The compressive properties of the three types of kenaf/glass hybrid and glass composites are shown in Fig. 3. The stress-strain relations of the hybrid composites began linearly and then experienced a sudden drop in stress before reaching the maximum point of stress, with the exception of the unidirectional kenaf hybrid composite. Thereafter, the stress increased again to the ultimate compressive strength, and finally a drastic drop in

load occurred. The drop in stress during compression testing was attributed to the failure of the kenaf fibers due to the breaking strength difference between glass and kenaf; load is also transferred to the glass fiber, which has a higher compressive strength compared to kenaf. The unidirectional kenaf hybrid composite possessed the highest set of compressive properties, but the results differed to a lesser extent: compressive strength was not dependent on fiber orientation. These results for kenaf/glass hybrid composites are comparable to previously studied composites (John and Naidu 2004; Reddy *et al.* 2008; Rao et al. 2009).

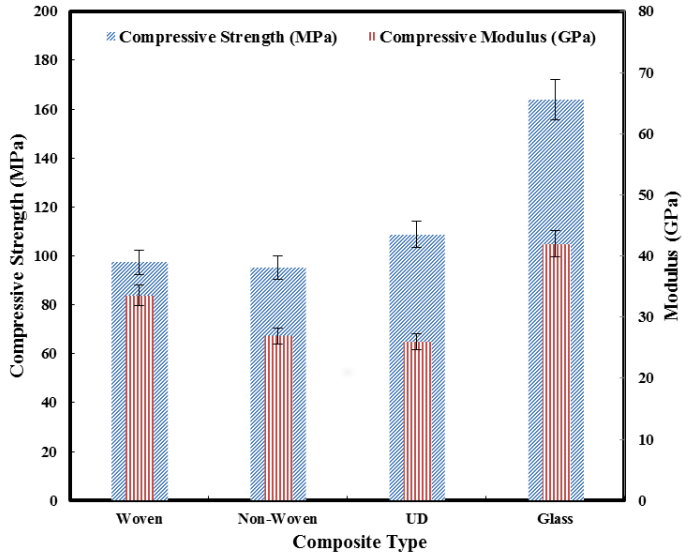

Fig. 3. Compressive properties of composites

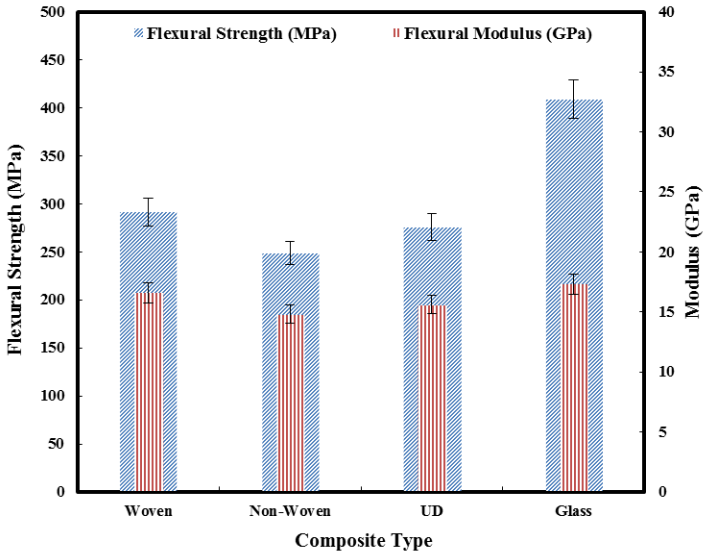

Fig. 4. Flexural properties of composites

The flexural strength and modulus of the composites constructed of axially, bi-axially, and randomly chopped strand kenaf fiber hybridized with plain-woven glass fiber and pure glass were evaluated (Fig. 4). The flexural strength and modulus were dependent on the fiber orientation; even though the shell fiber of the hybrid composites was the same,

the flexural properties of the final composite were affected. The woven kenaf hybrid composite offered the highest strength and modulus values compared with the other hybrid composites. A similar trend was reported in a study on the effect of fiber content and orientation on the mechanical properties of spall liner made of kenaf/Kevlar-reinforced epoxy hybrid composites (Yahaya *et al.* 2014a).

The flexural test showed a non-linear behavior for the hybrid composites that can be divided into three stages. The first stage was linear and gave a flexural modulus with few interruptions for UD kenaf, which is due to the single failure of single kenaf bundles. In the second stage, the load fell to a specific value and then rose again for a short period. This behavior is explained by the failure of kenaf fibers due to their low elongation value, which led to the first stage of failure. Finally, the remaining glass bundles started to carry the load but could only do so for a short time, resulting in complete composite failure.

Table 3. Static and Fatigue Properties of the Composites

Fiber Type	Tensile Strength (MPa)	Compressive Strength (MPa)	Flexural Strength (MPa)	Fatigue Coefficient *b*	Residual Stiffness Over 10^6 GPa	Fatigue Strength (MPa)
Woven	159.2±6.4	97.4±7.6	291.6±13.5	-0.06186	4.90	38.8
NW	109.3±4.6	95.1±5.4	248.8±12.4	-0.07938	-	-
UD	194.6±8.2	108.8±4.8	275.7±11.8	-0.06486	6.30	43.52
Glass	303.5±9.1	164±8.3	409±15.4	-0.05995	7.43	65.6

Fatigue

Based on the tensile and compression tests, a fully reversed cyclic fatigue test (tension-compression mode) was applied to the four composites at a stress ratio given by R = (-1) and a frequency of 10 Hz. Fatigue tests at different stress levels (percentage of ultimate compressive strength) as the maximum stress should not exceed the Ultimate Tensile Strength (UTS) or Ultimate Compressive Strength (UCS). In other words, failure follows the lower value, which is UCS. A Wohler stress-life (S-N) diagram showed that fatigue strength gradually declined with the increasing number of cycles (Fig. 5). A power-law regression equation (Eq. 3) was used to fit the experimental data and determine the fatigue coefficient (b) of the materials; this parameter represents the stiffness degradation rate per decade (decade = 10^1 to 10^2 cycle in logN) of material during fatigue loading. Table 3 presents the static and fatigue properties of the composites. The regression confidence levels were $R^2 \geq 0.94$, which was in good agreement with the experimental data. The general trend for composite fatigue was determined by matrix cracking and inter-laminar cracking. Matrix cracking occurred in the early stage, precisely in the first two decades, and the final failure was a single-kink failure similar to static failure. When a kink grew at a plane 45° to the loading direction (Fig. 9), the specimen failed due to pure in-plane shear resulting from sliding of the specimen halves (Shah *et al.* 2013). Normalized S-N diagrams showed that the hybrids with woven and unidirectional kenaf composites shared almost the same fatigue coefficients, with a stiffness degradation rate of 6.2% and 6.5% per decade and fatigue strength of 38.8 MPa and 43.5 MPa, respectively (Fig. 6). However, a flatter S-N slope was observed for both hybrids, which was reflected by more data scattering in the unidirectional hybrid diagram and more consistent fatigue in the woven one.

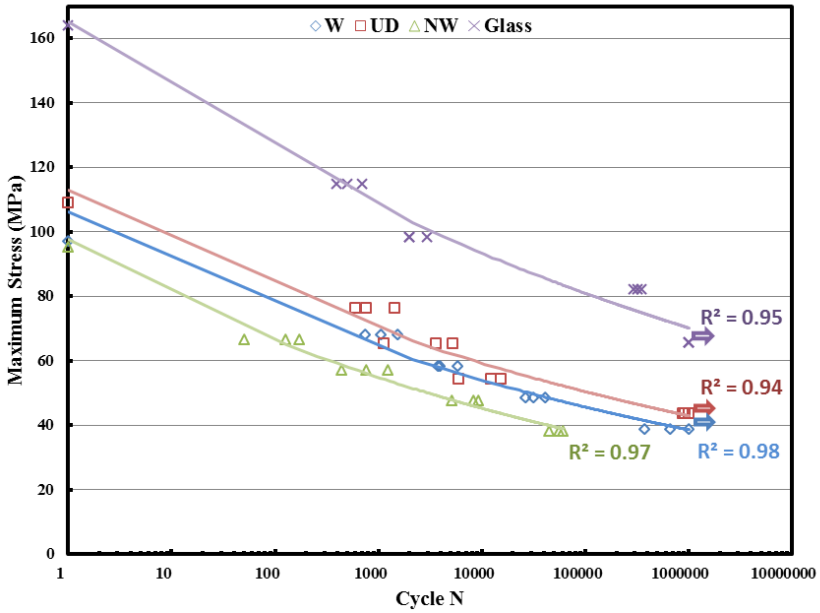

Fig. 5. S-N curves for composites fitted by power regression with R^2 ≥ 0.94. The arrowheads indicate that these samples survived 1 million cycles.

This difference could be due to the high warp and weft density value of the woven kenaf, which was 890 g/m^2 (Salman *et al.* 2015b) and has a significant effect on the mechanical properties of the final composites (Demircan *et al.* 2015). In contrast, the mat kenaf hybrid composite had a lower fatigue degradation rate of 8% due to a lack of fiber interlocking, poor adhesion as delamination area was larger, high void content, and finally a slightly different failure mode compared to the other composites. The glass-based composites showed a steeper S-N diagram, which led to a more significant decrease in fatigue strength. In one study comparing the S-N curves of bidirectional flax and glass, glass had a steeper curve than flax composites (Liang *et al.* 2012).

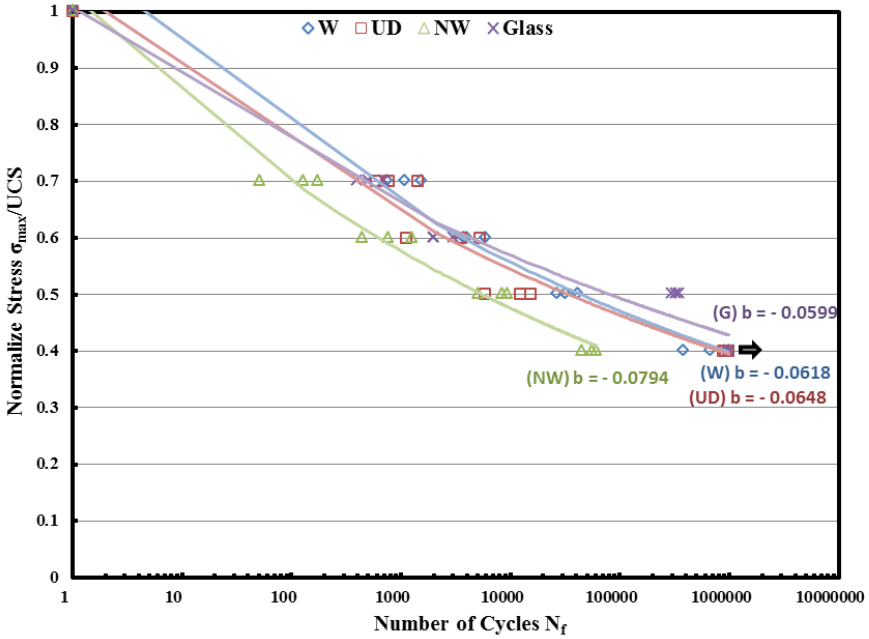

Fig. 6. Normalized S-N curves of composites

The trends in stiffness degradation for the composites at a stress level of 50% of UCS were evaluated (Fig. 7). Glass had the highest rate of degradation, followed by the kenaf-mat hybrid composite, while the woven kenaf hybrid had the lowest value. The residual dynamic elastic modulus and the magnitude of fatigue strength of the specimens that survived after 1 million cycles, *i.e.*, glass, woven kenaf, and unidirectional hybrid, are shown in Table 3 and Fig. 8.

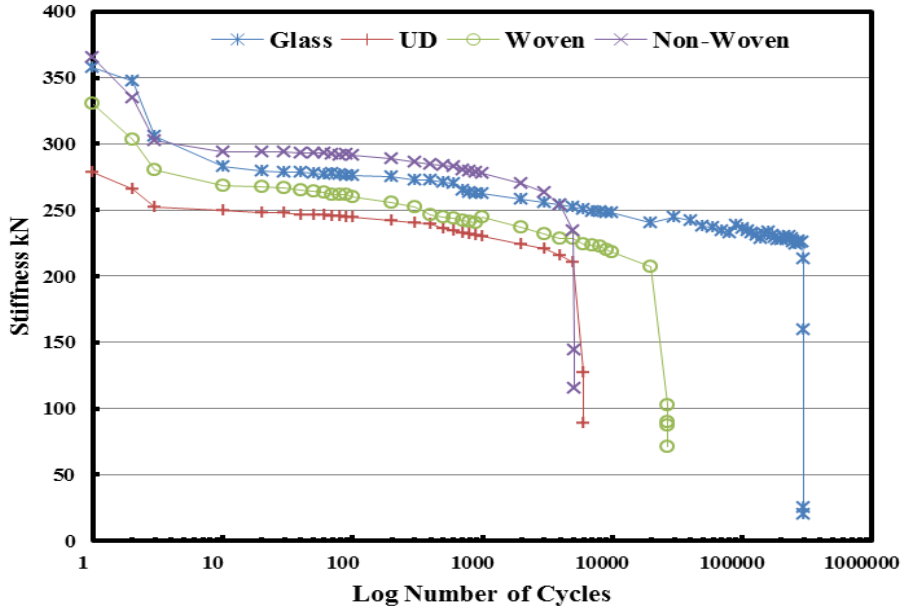

Fig. 7. Stiffness-cycle relationships at 50% of UCS

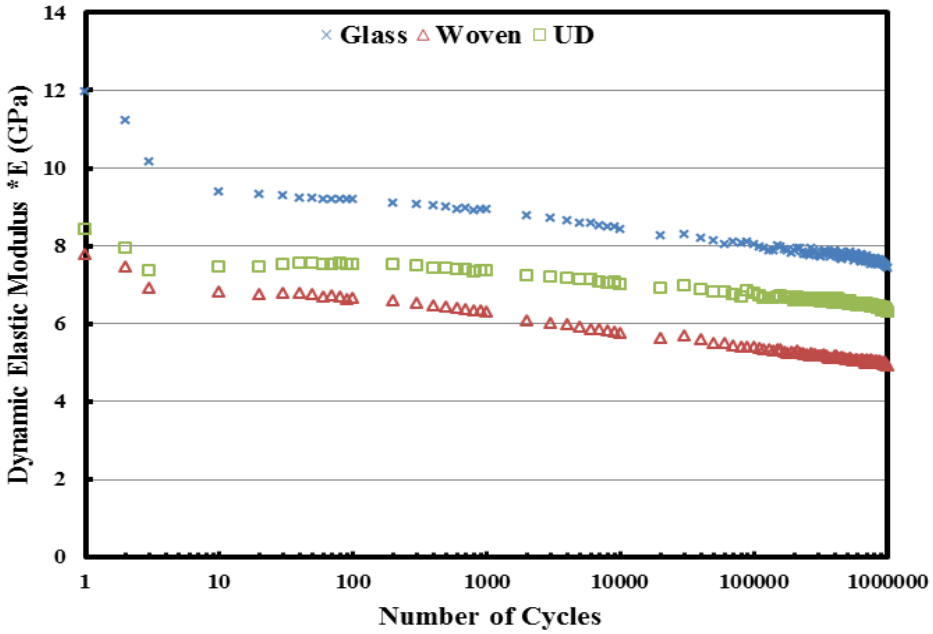

Fig. 8. The residual dynamic elastic modulus of specimens surviving 10^6 cycles

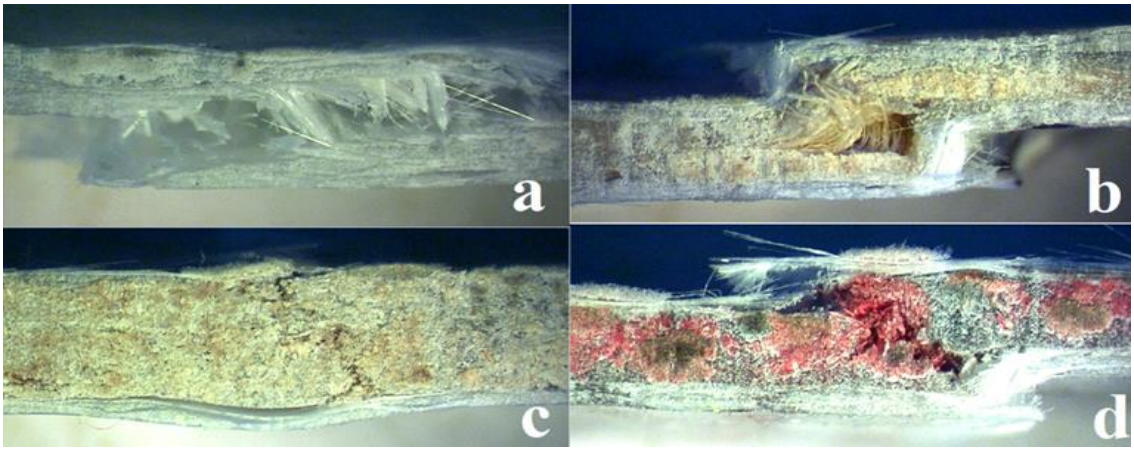

Fig. 9. Typical failure modes under tension-compression load of (a) pure glass, (b) unidirectional kenaf/glass, (c) non-woven kenaf mat/glass, and (d) woven kenaf /glass composites

Plotting dynamic elastic modulus degradation with a normalized number of cycles under a stress level of 50% UCS allowed comparison of the behavior of the materials during their lifetime (Fig. 10).

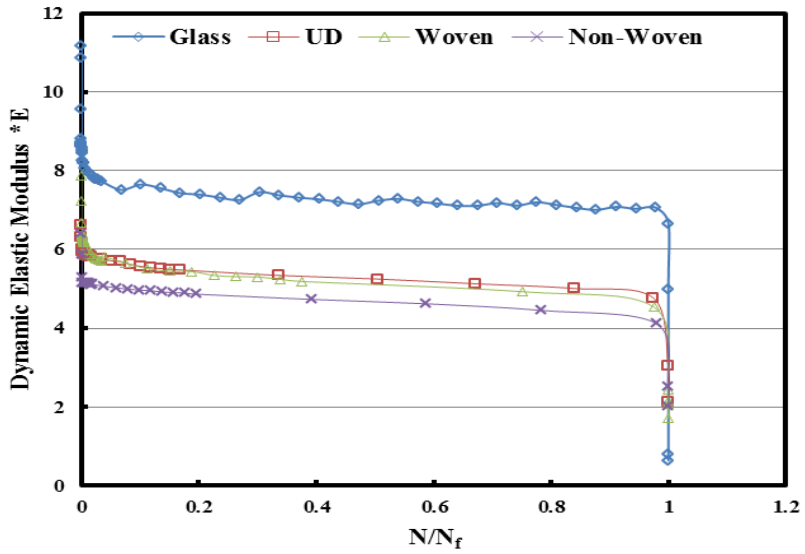

Fig. 10. Dynamic elastic modulus and normalized number of cycles of the composites at 50% of UCS

All composites showed three stages during fatigue. The first stage presented a gradual degradation with minor variation in its rate until 20% N_f, which was caused by the matrix cracking failure mode. The second stage was almost stable in stiffness, and the loading transferred from the matrix to the fibers. The third stage included sudden failure due to fiber breakage and single kink failure shape. According to the standard test, the specimen temperature should be monitored during fatigue loading (ISO 2003); the results are more accurate when an IR-camera is used to observe the temperature and when the hot zones of coupon are recognized. The temperatures of the coupon were recorded at a rate of one image per 500 cycles until heat stability was reached at 10000 cycles (Montesano *et al.* 2015). A laser thermometer has low accuracy because it records the temperature at only

one point. The heat generated due to fatigue loading was within the acceptable rate, which should not exceed 10 ºC over the initial temperature (Gassan and Bledzki 1999). In addition, kenaf orientation affected the temperature of the hybrid composites; kenaf mat showed the highest heat rate, followed by woven and unidirectional kenaf (Fig. 11). This observation was attributed to the natural fiber areal density, in which higher the areal density is linked to more heat.

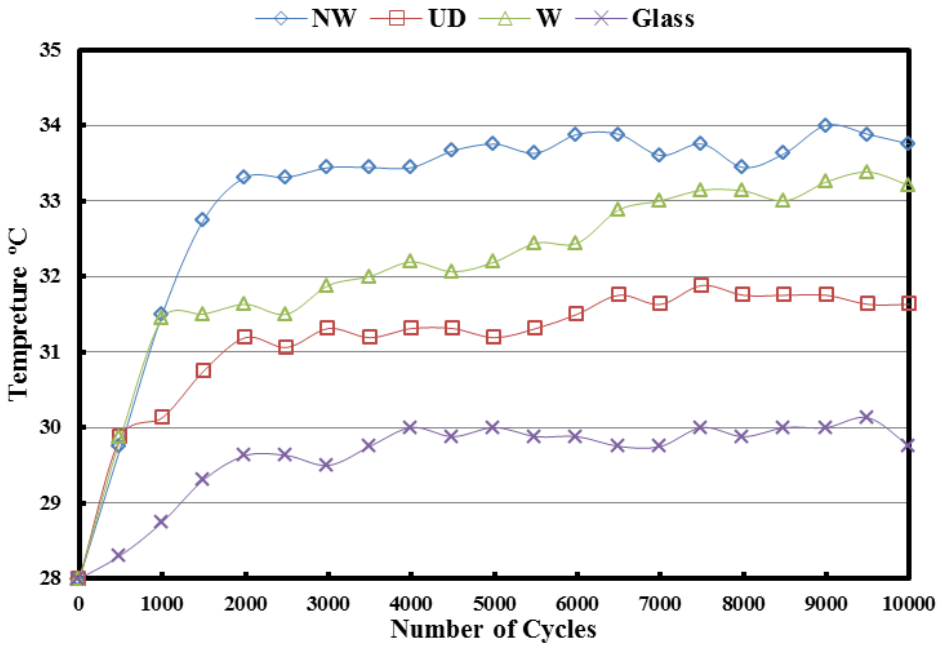

Fig. 11. Surface temperature variations for the composites during fatigue testing

Morphological Properties

Micrographs of the three types of kenaf hybrid composites show the tensile failure surfaces (Fig. 12). The failure modes of the non-woven kenaf hybrid composites were brittle. The matrix failure and fiber pullout was high compared with the unidirectional and woven kenaf, which is explained by its short fiber length, low adhesion, and absence of fiber interlocking. These properties lead to the matrix and glass fibers being the main load carriers compared with the kenaf fiber, as shown in Fig. 12a. The delamination between the kenaf and the glass was greater and more noticeable than in the other hybrid composites. These observations corroborate the low mechanical properties of the non-woven kenaf hybrid composites.

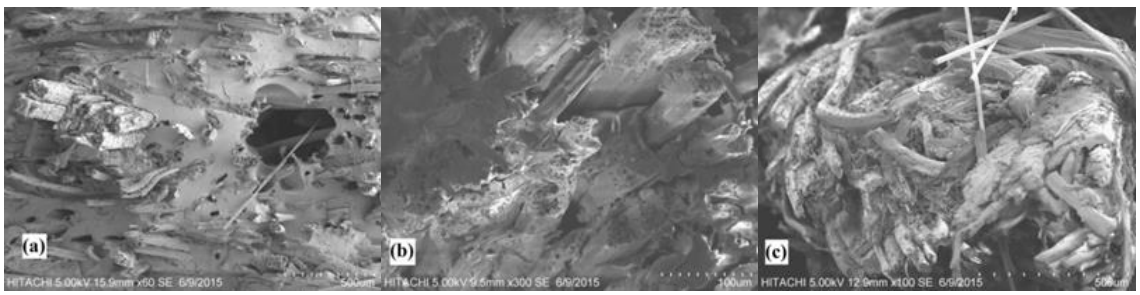

Fig. 12. Micrographs of tensile failure sections of kenaf hybrid composites: (a) non-woven mat, (b) plain woven, and (c) unidirectional twisted yarns

Figure 12b depicts the failure surface of the woven kenaf hybrid composite due to tension loading. The different modes of failure were due to high interlocking strength of the wrap and weft yarns. The similarity between the kenaf and glass structure was advantageous for resisting load efficiently. The modes of failure observed in the micrographs show that both the fiber and matrix were the load carriers; this effect can explained by the existence of matrix cracks, matrix debonding, fiber breakage, less fiber pullout, and less delamination between the fibers. A similar failure behavior was noted in the unidirectional kenaf hybrid composites, but in the axial direction only. The kenaf yarn concentration in the axial direction provides higher tensile strength in the unidirectional kenaf hybrid composites. Generally, glass fiber was the superior load carrier; micrographs showed the same fiber pullout and fiber-breakage failure modes in all of the hybrid composites.

CONCLUSIONS

1. Kenaf fiber was hybridized in different alignments with plain woven glass-reinforced unsaturated polyester. The tensile strength, compression, flexural strength, and fully reversed fatigue loading of the composites were tested.
2. The monotonic and fatigue properties of kenaf/glass hybrid composites depended on kenaf fiber orientation, which dramatically affected the composite properties.
3. The non-woven random mat kenaf hybrid composite exhibited poor mechanical and fatigue properties compared with the other composites. Its low strain, brittleness, and short fiber length had a noticeable effect on its physical and fatigue properties.
4. Hybridization with UD and woven kenaf fibers improved the fatigue degradation coefficient of composites. The coefficients were 6.2% and 6.4% for the woven and unidirectional kenaf, respectively, compared with 7.9% for non-woven hybrid.
5. All composite surface temperatures were within the acceptable range during fatigue loading. Small temperature differences were attributed to the different orientations and areal densities of the fibers.
6. The woven kenaf hybrid composite is a low-weight, eco-friendly material that has a considerable balance in static and fatigue strengths with low fatigue sensitivity in bidirectional planes compared to glass. Thus, it is strongly recommended for structural applications.

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